Summary

Human behavior is initially goal-directed involving the anticipation of future outcomes, with increasing practice, however, behavior is thought to become less governed by outcome anticipation and instead more directly driven by the antecedent stimuli, hence becoming increasingly habitual (Dickinson, 1985). On the neural level, traditionally, goal-directed and habitual behaviors are assumed to be supported by separate, albeit interacting, networks. A large body of research has demonstrated that goal-directed behavior relies on several key regions, notably the angular gyrus (AG) (Liljeholm et al., 2015; Zwosta et al., 2015) and the (anterior) caudate nucleus (de Wit et al., 2012; Zwosta et al., 2015). On the other hand, the formation of habitual responding are assumed to be related to the key regions in sensorimotor network, such as the posterior putamen and the premotor cortex (PMC) (de Wit et al., 2012; Tricomi et al., 2009). However, Zwosta et al. (2018) found that stronger habits were associated with a stronger decrease in activity of AG. Furthermore, ongoing training was accompanied by increasing functional connectivity between posterior putamen and PMC, however, this changed connectivity was not predictive of habit strength. Interestingly, this null-finding is in line with other recent studies (Gera et al., 2023; van Timmeren et al., 2024) suggesting that in humans the expression of habitual behavior seems more indirectly controlled by the goal-directed system rather than directly controlled by the sensorimotor system. Considering the currently mixed and also solely correlational evidence, the current dissertation aims to (re-) investigate the contribution as well as the potential causal role of goal-directed and sensorimotor brain systems in habit formation using different multivariate functional connectivity analysis methods and repetitive transcranial magnetic stimulation (rTMS) as a non-invasive brain stimulation technique.

The first key question addressed by this dissertation was whether the puzzling absence of a significant association between habit strength and regions of the brain's 'habit system' might somehow be due to the chosen type of analysis. Specifically, I reasoned that the analytical focus on local brain activity or univariate functional connectivity measures might be too narrow. For instance, the focus on isolated connectivity changes between individual pairs of brain regions such as between PMC and putamen might only account for a small part of a global neural re-organization process and might therefore fail to predict individual habit strength. Therefore, in **study 1** (Wang et al., 2022), I examined whether learning-related functional connectivity alterations distributed across the whole brain could predict individual habit strength by applying Elastic Net multiple regression on the original Zwosta et al. (2018) dataset. In this study, I demonstrate the relevance of global functional network properties for predicting the behavioral expression of habits. Further post hoc examination highlighted that the PMC within the sensorimotor system concentrated most of the predictive power. Together, these results established a significant role of the sensorimotor system in habit formation and thereby complements previous correlational evidence highlighting the relevance of the goal-directed system in habit formation (Zwosta et al., 2018). Yet, the important question of causality still remains open. Specifically, in **study 2,** I therefore aimed to probe the causal role of these two antagonistic brain systems during habit formation to investigate whether it causally relied on a decreasing involvement of the goal-directed or an increasing involvement of the habitual system, or both. In **study 2,** I used rTMS with AG and PMC as separate goal- and habit-related stimulation targets. As hypothesized, TMS differentially affected the habit expression. Specifically, TMS increased habit strength when the goal-directed system was disturbed by targeting the AG. By contrast TMS numerically reduced habit strength when the habit-related brain system was disturbed by targeting PMC, but this effect did not reach statistical significance. **Study 1** and **2** demonstrated that habit formation is associated with both the goal-directed and habit-related brain systems, with the causal role of the former highlighted through TMS. The final **study 3** (Wang et al., 2024) took a different perspective going beyond the analysis of functional connectivity changes centered on circumscribed functional brain networks (here: goal-directed and habit-related networks). Previous studies have shown that learning-related behavioral changes were associated with increasing brain network segregation (Bassett et al., 2015). However, it still remains unclear whether the kind of goal-habit transition as investigated in **studies 1** and **2** might also be associated with such functional brain network segregation. Importantly, to demonstrate the generalizability and robustness, I performed all the analyses across two separate studies. In both studies, the results indicated that a higher learning rate is associated with more rapid brain network segregation. However, there was no significant correlation between habit strength and changes in brain network segregation.

In summary, compared to previous univariate yet correlational fMRI results, I demonstrated more comprehensive and causal evidence of the neural processes involved in habit formation by using multivariate analysis methods and the TMS technique. First, I successfully showed that connectivity changes within the sensorimotor network, particularly centered on the PMC, were associated with habit strength. However, the causal relationship between the sensorimotor network (targeting the PMC) and habit strength was not robust, even though rTMS numerically reduced habit strength. In contrast, I found a significant increase in habit strength when the goal-directed system was disrupted by targeting the IPL. Second, using the network modularity algorithm, I demonstrated that habit formation is also accompanied by an increasingly segregated brain state, which was associated with the initial goal-directed learning processes but not with habit formation. Hence, in summary, these present findings align with a number of recent study results highlighting the relevance of the goal-directed system for the expression of habits.